Search for Dark Matter in ANTARES and KM3NeT

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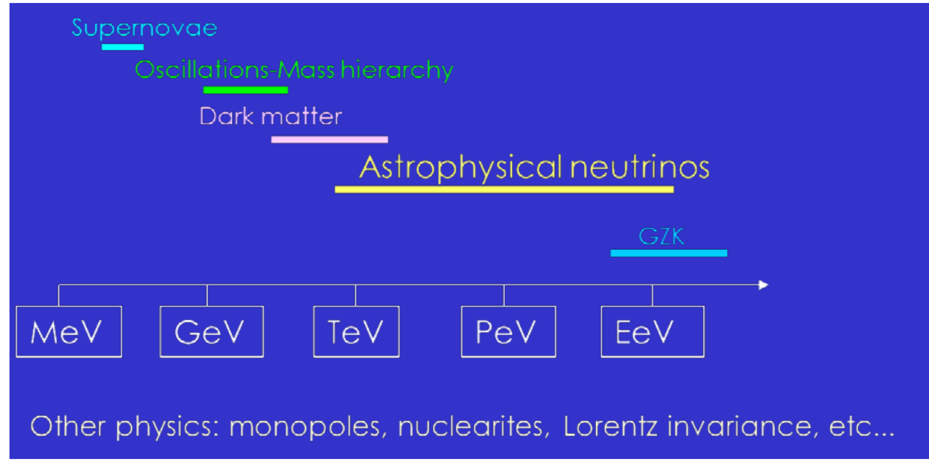
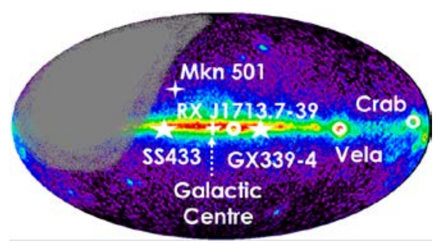
RENATA Thematic Meeting on Dark Matter, 5-7 February 2018, LSC

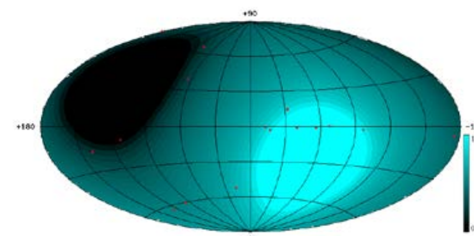
Mediterranean Neutrino Telescopes

- **Physics motivation and Detection principle**
  - High energy ν astronomy and neutrino properties
  - Large volume of transparent medium surveyed by PMTs

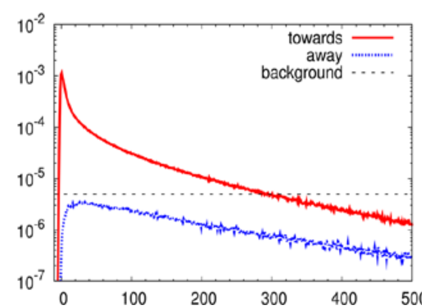


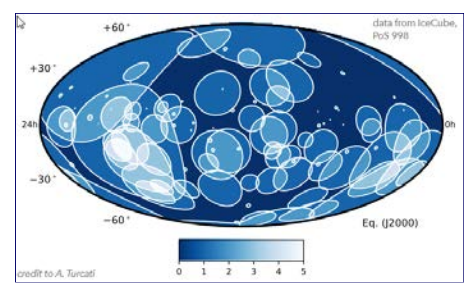
- **Location:**
  - Northern terrestrial hemisphere:
  - Complementary to IceCube
  - Golden channel for southern sky sources. "Milky-Way optimized"





- **Medium:**
  - Deep Sea water
  - Very small light scattering (good angular resolution even for showers)
  - Natural backgrounds (^{40}K and biolum) can be handled.





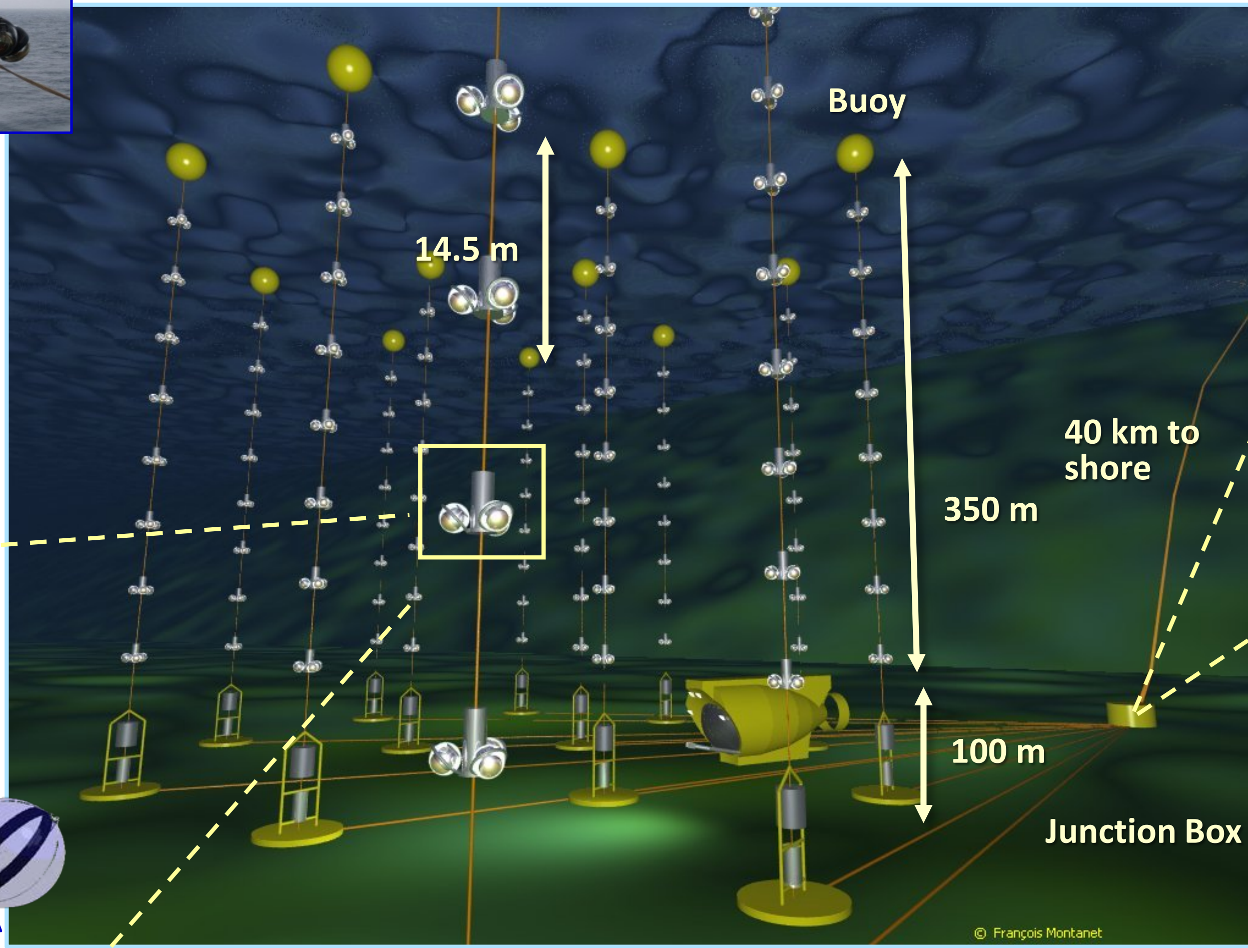
Antares and KM3NeT Collaborations

ANTARES

LED Beacon

Hydrophone

Optical Modules 10” PMT



12 lines (885 PMTs)

25 storeys / line

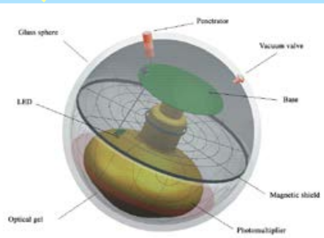
3 PMTs / storey

5-line setup in 2007

Completed in 2008

Junction Box

Shore station



Mediterranean Sea (near Toulon) at **2500 m** depth

NIM **A484** (2002) 369, AP **19** (2003) 253
AP **23** (2005) 131, NIM **A555** (2005) 132
AP **26** (2006) 314, NIM **A570** (2007) 107
NIM **A578** (2007) 498,NIM **A581** (2007) 695
AP **31** (2009) 277, NIM **A622** (2010) 59-73
AP **34** (2011) 539, NIM **A656** (2011) 11

AAS Nova (of the AAS Journals) featured our latest paper!

AAS NOVA Research highlights from the journals of the American Astronomical Society

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A Nine-Year Hunt for Neutrinos

By Susanna Kohler on 31 January 2018 FEATURES

Share:

Artist's representation of the ANTARES neutrino detector, made up of 12 strings of photomultipliers that detect and amplify the light emitted by charged particles produced by rare neutrino interactions. [ANTARES]

How do we hunt for elusive neutrinos emitted by distant astrophysical sources? Submerge a huge observatory under ice or water … and then wait patiently.

RELATED HIGHLIGHTS

1 December 2017 FEATURES
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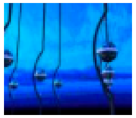
9 October 2017 FEATURES
The Prospect of Neutrinos with Gravitational Waves

8 August 2017 ASTROBITES
Where Are the IceCube Neutrinos Coming From?



16 May 2017 ASTROBITES
The Origin of the IceCube Neutrinos: An Ongoing Mystery

7 February 2017 ASTROBITES
Anisotropies in Our Galaxy

KM3NeT

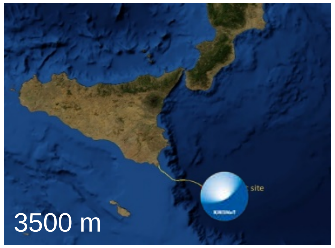
❖ ARCA (Astronomy)
- Building Block:
  - 115 strings
  - 18 DOMs / string
  - 31 PMTs / DOM
  - Total: 64k*3¨ PMTs

❖ ORCA (NMH+ ν properties)
- Same technology, denser layout

	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	5.7 Mton	0.6*2 Gton

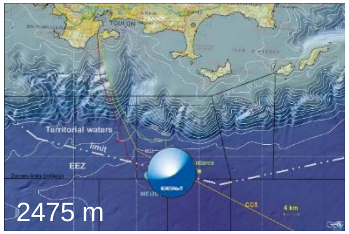
❖ Stages:
- Phase 1: 24 ARCA + 7 ORCA strings (already funded, being deployed)
- KM3NeT 2.0: 2 ARCA +1 ORCA blocks (~50% funded)
  Blessings: ESFRI and APPEC
- Phase 3: 6 ARCA + 1 ORCA blocks

ARCA
Astroparticle **R**esearch with **C**osmics In the **A**byss

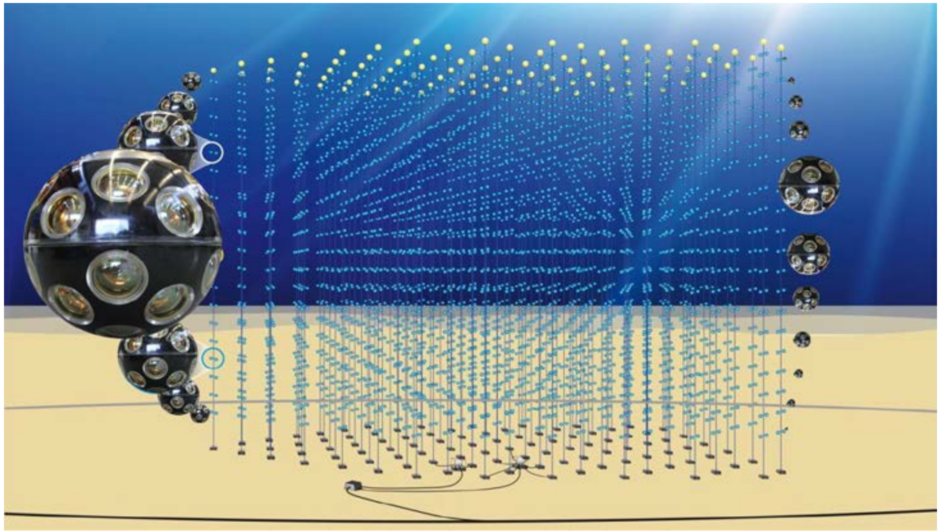


Capo Passero, Sicily, Italy

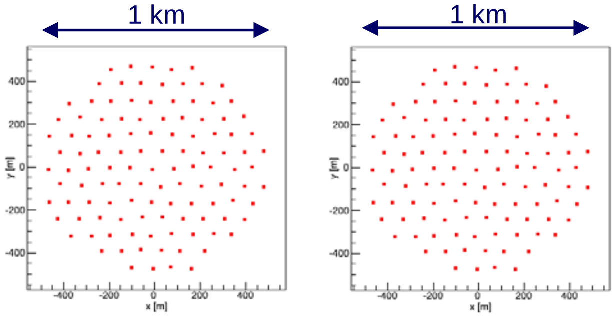
ORCA
Oscillation **R**esearch with **C**osmics in the **A**byss



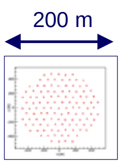
Toulon, Var, France



ARCA



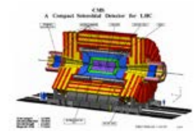
ORCA



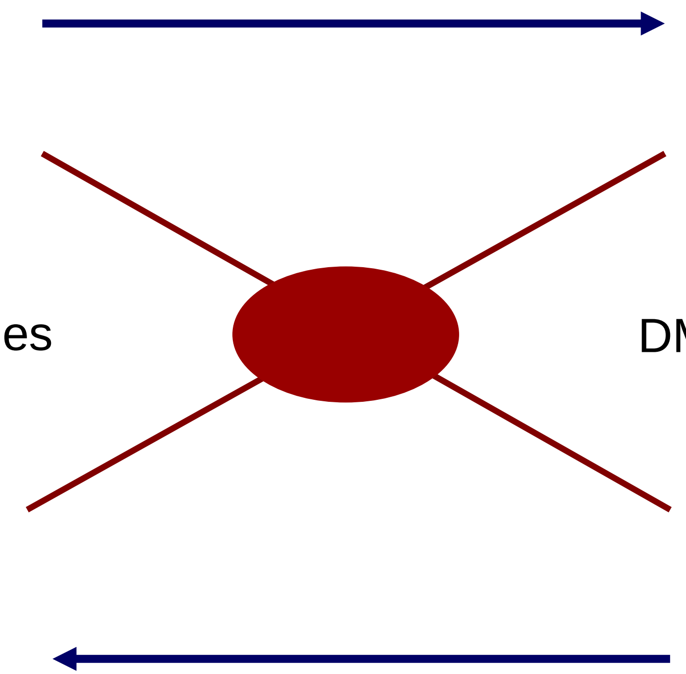
How to detect WIMPs

ATLAS

CMS



Production



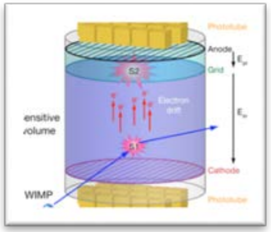
SM particles

DM particles

Direct Detection

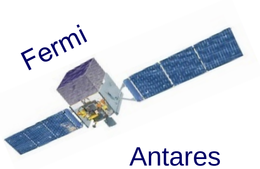
Annihilation
(Indirect detection)

XENON 1T

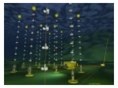


LUX

PICO



Antares



HESS

IceCube

Magic

All the methods are needed to make sure we have detected dark matter

Dark matter searches with ν-telescopes

- Sun
- Galactic Centre and Halo

Not covered:
Earth, dwarf galaxies, galaxy clusters, monochromatic ν's, others…

Dark Matter Solar Neutrino Search

WIMP capture in the Sun

- WIMPs can be scattered by the Sun nuclei and loose enough energy to become gravitationally trapped.
- Once trapped further scattering takes place and they tend to concentrate in the Sun's core.
- WIMP self-annihilation will produce SM particles which in turn will give rise to neutrinos.
- WIMP capture and annihilation reach an equilibrium.

Advantages of the solar DM Search

- In the Sun a signal would be very clean. The Sun does emit neutrinos, but they are low energy (*)
- The Sun journey through the Galaxy makes it less sensitive to non-uniformities in the local dark matter density.
- The Sun is mainly composed of hydrogen, this gives us information about spin–dependent cross-sections.
- Rates depend only weakly on WIMP velocity distribution.
- The Sun is massive enough and not too far away.

(*) More about CR induce background later

WIMP Capture rate

Capture rate in a given Sun's shell of volume *dV*:

$$u_{max} = 2\frac{\sqrt{M_i m_\chi}}{m_\chi - M_i} v_{esc}$$

velocity distribution

elastic scattering X-section WIMP-nucleus type ***i***

WIMP density

$$\frac{dC_i}{dV} = \int_0^{u_{max}} du \int d\Omega_w \; f(u)\, u\, w^2\, \sigma_i\, n_i \frac{\rho_\chi}{m_\chi}$$

$$w = \sqrt{u^2 + v_{esc}^2}$$

Number density nucleus type ***i***

WIMP mass

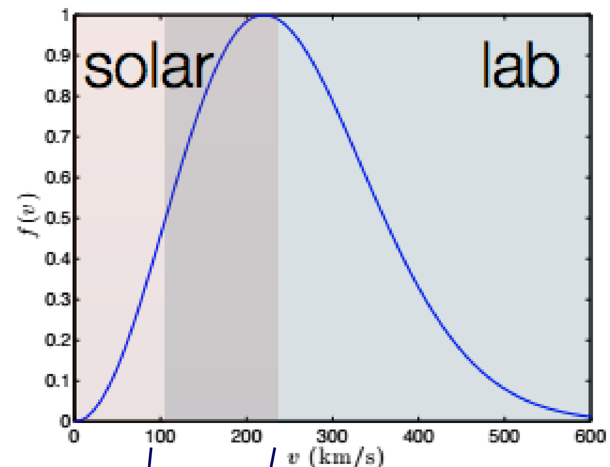
Sum over shells:

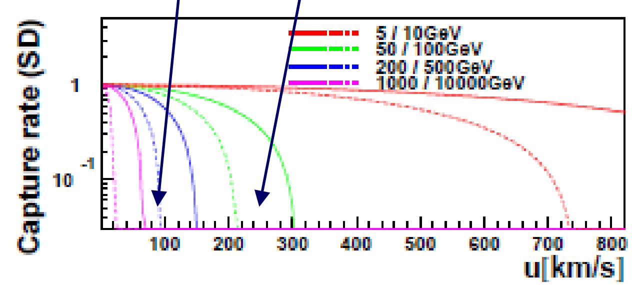
$$C = \int_0^{R_\odot} 4\pi r^2 dr \sum_i \frac{dC_i(r)}{dV}$$

A Maxwellian velocity distribution is assumed:

$$f(u) = \sqrt{\frac{3}{2\pi}} \frac{u}{v_\odot v_{rms}} \left[\exp\left(-\frac{3(u-v_\odot)^2}{2v_{rms}^2}\right) - \exp\left(-\frac{3(u+v_\odot)^2}{2v_{rms}^2}\right)\right]$$

Other v distributions: <20% change in C Choi et al. JCAP 1405 (2014) 049





Lower velocities → higher capture rate (indirect)

Higher velocities → larger recoils (direct)

Neutrino flux and annihilation rate

The number of WIMPs depends on capture and annihilation rates:

$$\frac{dN}{dt} = C_{cap} - C_{ann} N^2$$

If we assume that equilibrium has been reached :
(T_{Sun} = 4.5 x 10^9 years)

$$\Gamma_{ann} = \frac{1}{2} C_{cap}$$

The neutrino flux depends on the annihilation rate:

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\Gamma_{ann}}{4\pi d^2} \frac{dN_\nu}{dE_\nu}$$

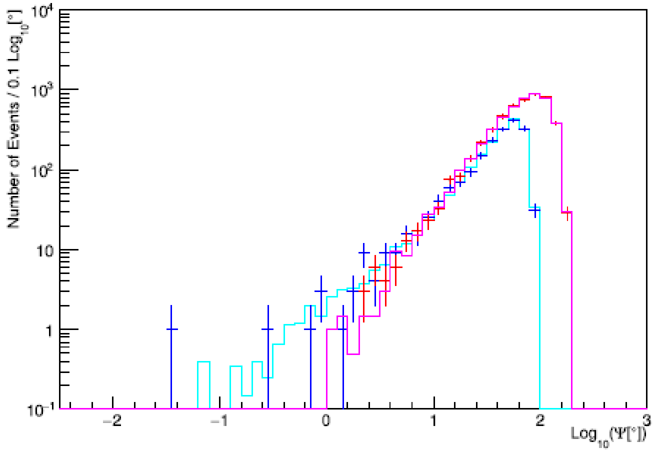
Capture rate depends on the WIMP-nucleon cross-section
(and on WIMP mass, density and velocity)

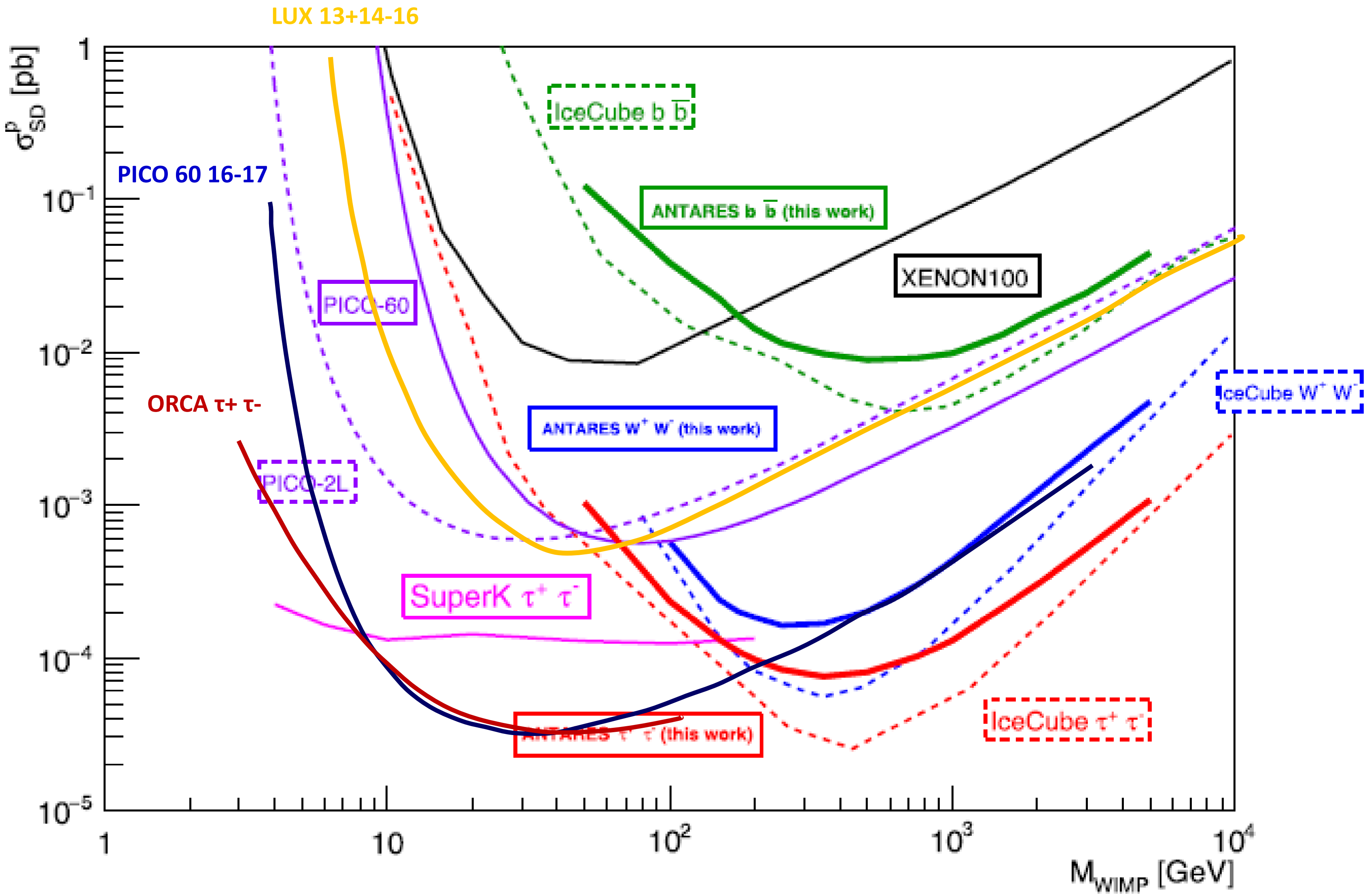
$$C_{cap} = 3.35 \times 10^{18}\ s^{-1} \times \left(\frac{\rho_{local}}{0.3\ GeV\ cm^{-3}}\right) \times \left(\frac{\sigma_{H,SD}}{10^{-6}}\right)$$
$$\times \times \left(\frac{270\ km\ s^{-1}}{v_{local}}\right) \times \left(\frac{TeV}{M_{WIMP}}\right)^2$$

Antares – Solar Search

- Antares data 2007-2012
- Upgoing, ν_μ events.
- Signal simulation of representative channels: $\chi\chi \rightarrow WW$, $\tau\tau$ (hard) and bb (soft).
  χ capture+annihilation+ ν production+ +interaction+propagation DarkSUSY and WimpSim
- Cuts on track reconstruction quality used to reject background. Two reconstruction strategies.
- Likelihood ratio as a function of angle to the Sun.

JCAP 11 (2013) 032
PL B 759 (2016) 69)




LUX 13+14-16
PICO 60 16-17
ORCA τ+ τ-
IceCube b b̄
ANTARES b b̄ (this work)
XENON100
PICO-60
PICO-2L
ANTARES W⁺ W⁻ (this work)
IceCube W⁺ W⁻
SuperK τ⁺ τ⁻
ANTARES τ⁺ τ⁻ (this work)
IceCube τ⁺ τ⁻
σ^p_SD [pb]
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
1
10
10²
10³
10⁴
M_WIMP [GeV]

DM in the Sun – Issues

- **Has equilibrium been reached?**
  - For $\langle\sigma_A v\rangle \sim 10^{-26}$ cm^3 s^{-1}, equilibrium time as large as the age of the Sun only for σ^{SD} as low as 10^{-42} cm^2

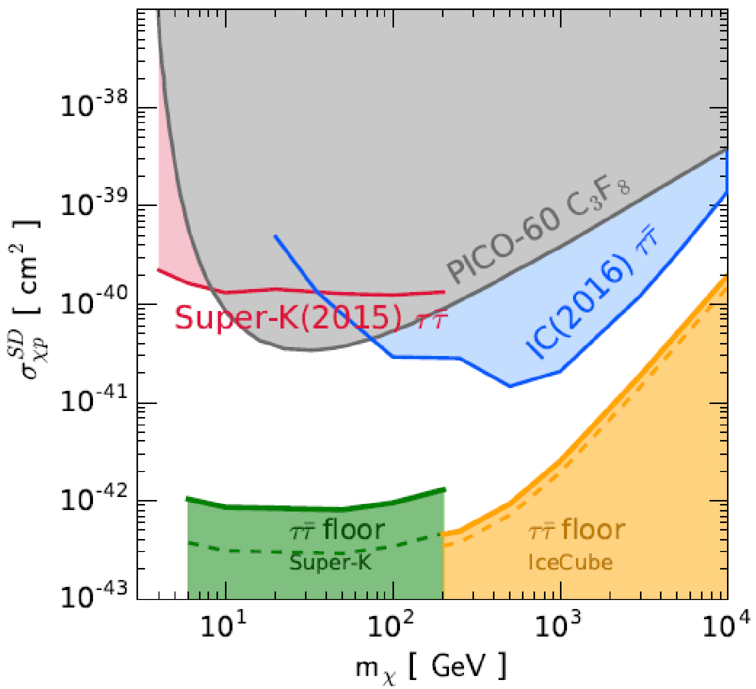
- **Is the velocity distribution critical?**
  - Uncertainty on DM velocity has an influence of no more than ~50% on the limits.

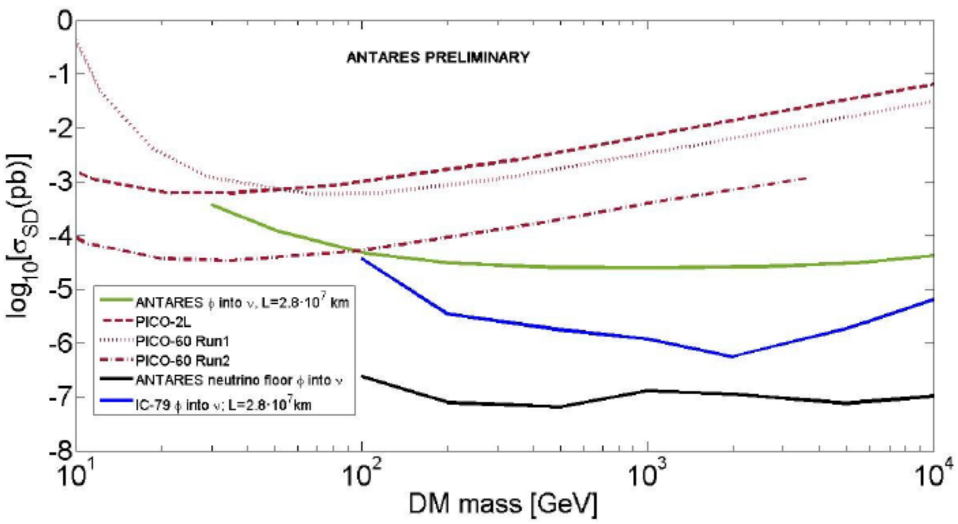
- **If the dark matter is in a dark disk?**
  - This will improve limits! A population of lower velocities DM particles will enhance the capture rate (under some assumptions as much as x 20!).

- **In some scenarios, direct detection will have a hard time…**
  - Non-relativistic effective theory classifies possible non-relativistic interactions
  - DM-nucleon scattering may be velocity / momentum dependent and suppressed at non-relativistic energies
  - Enhances SD x-section for light nuclei
  - Sun has other nuclei (different proton-neutron composition) sensitive to various operators

$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$	$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$	$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$	$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$

DM Sun – CR Background





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C. A. Argüelles, G. de Wasseige, A. Fedynitch, and B. J. P. Jones, JCAP 7 (2017) 024
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K. C. Y. Ng, J. F. Beacom, A. H. G. Peter, and C. Rott, Phys.Rev. D96 (2017) 103006

M. Masip, Astrop. Phys. 97 (2018) January arXiv:1706.01290

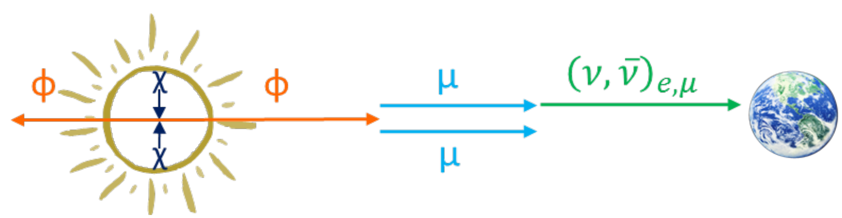
M. Ardid, I. Felis, M. Lotze, Ch. Tönnis, PoS (ICRC 2017) 907

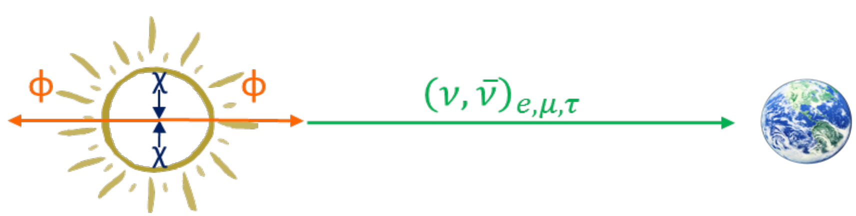
Secluded Dark Matter

- DM is secluded from SM matter. DM WIMP annihilation proceeds via a metastable mediator ϕ.

  May explain the e+/e- ratio of Pamela, Fermi and AMS while retaining thermal relic WIMP scenario.

- In many models ϕ decays to leptons near the Earth. ν-telescopes can detect muons:
  - direct detection of dimuons
  - neutrinos from dimuons from mediator
  - neutrinos directly from mediator.

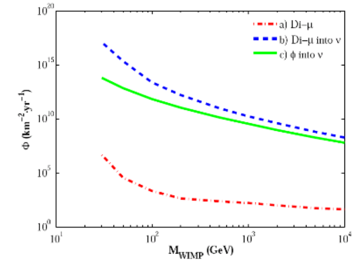


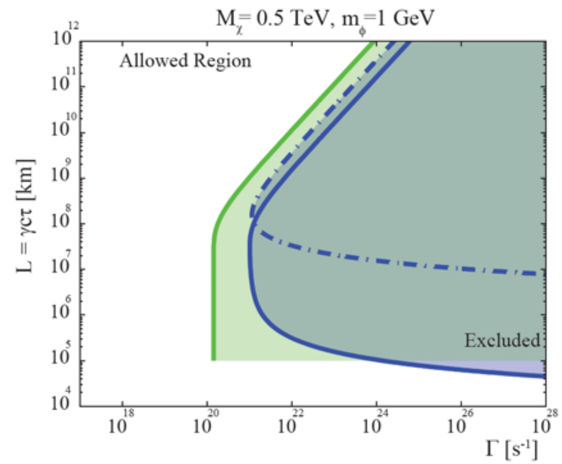


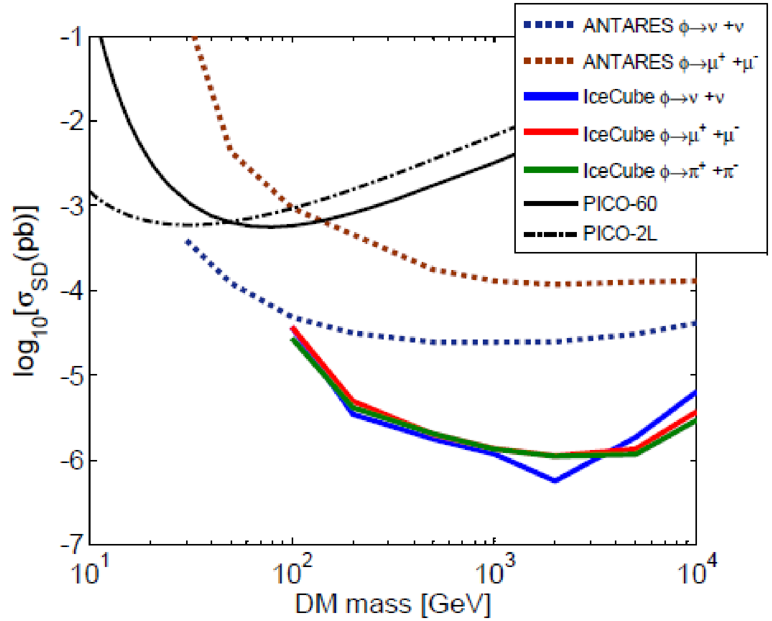
Secluded DM – σ limits

- Limits on fluxes can be translated to regions of decay length vs annihilation rate
- Limits on the WIMP-nucleon SD and SI cross-sections can be set. For sufficiently long-lived but unstable mediators, the limits are competitive.
- Limits from IC79, obtained by Miquel Ardid et al.
- Some specific models can be constrained, e.g. "dark photons" (gauge boson of a broken U(1) symmetry that mixes with SM gauge bosons).

Flux limits







Antares, JCAP 05 (2015) 016 arXiv:1602.07000

M. Ardid et al., JCAP04 (2017) 010

Galactic Centre

and

Halo

Neutrino flux

The neutrino flux (per solid angle) in a solid angle ΔΩ is given by:

Product of self-annihilation cross-section times WIMP velocity averaged over the velocity distribution

Neutrino energy spectrum per annihilation.

$$\frac{d\Phi_{\Delta\Omega}}{dE} = \frac{\langle \sigma_A v \rangle}{2} J_{\Delta\Omega} \frac{1}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

Intensity (flux per solid angle) along the line of sight of the DM density squared (see next slide).

WIMP mass squared

$J(\psi)$ – Line of sight integral

Intensity (flux per solid angle) at an angle ψ with respect to the GC direction is proportional to the line of sight integration of the DM density squared:

$$J(\psi) = \int_0^{l_{max}} \rho_{DM}^2 \sqrt{R_{sc}^2 - 2lR_{sc}\cos\psi + l^2}\, dl$$

where: $l_{max} = \sqrt{R_{Gal}^2 - R_{SC}^2 \sin^2\psi} + R_{SC}\cos\psi$

the radius of the solar circle and that of the Galaxy are $R_{SC} \approx 8.5$ kpc and $R_{Gal} \approx 50$ kpc

If we are looking at the Galactic centre in a cone with half-angle ψ around the GC, which has a field of view of $\Delta\Omega = 2\pi(1 - \cos\psi)$:

$$J_{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_{\cos\psi'}^{1} J(\psi')\, 2\pi\, d(\cos\psi')$$

Halo DM density

NFW

$$\rho_{NSFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

Burkert

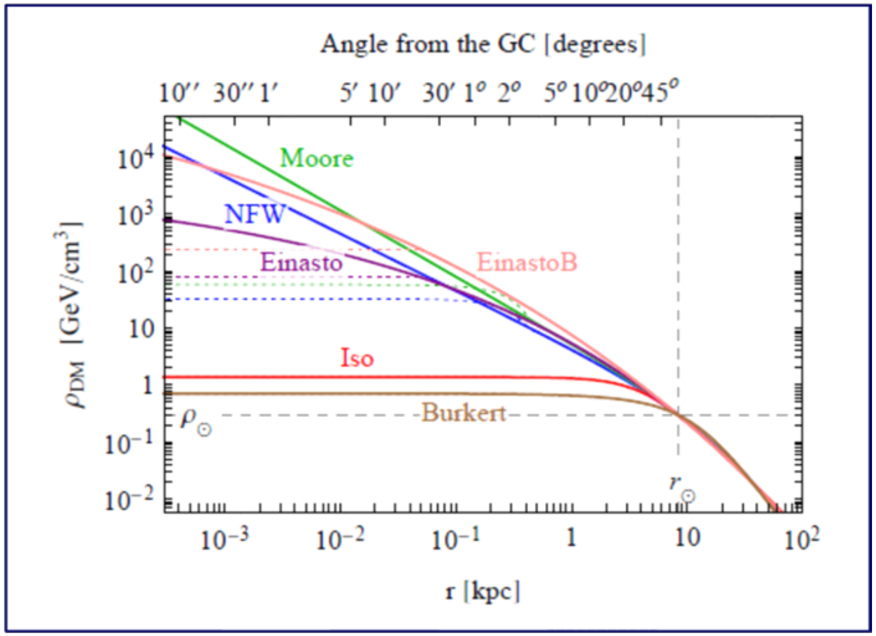
$$\rho_{Bur}(r) = \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)\left(1+\left(\frac{r}{r_s}\right)^2\right)}$$

Isothermal

$$\rho_{Iso}(r) = \frac{\rho_s}{1+\left(\frac{r}{r_s}\right)^2}$$

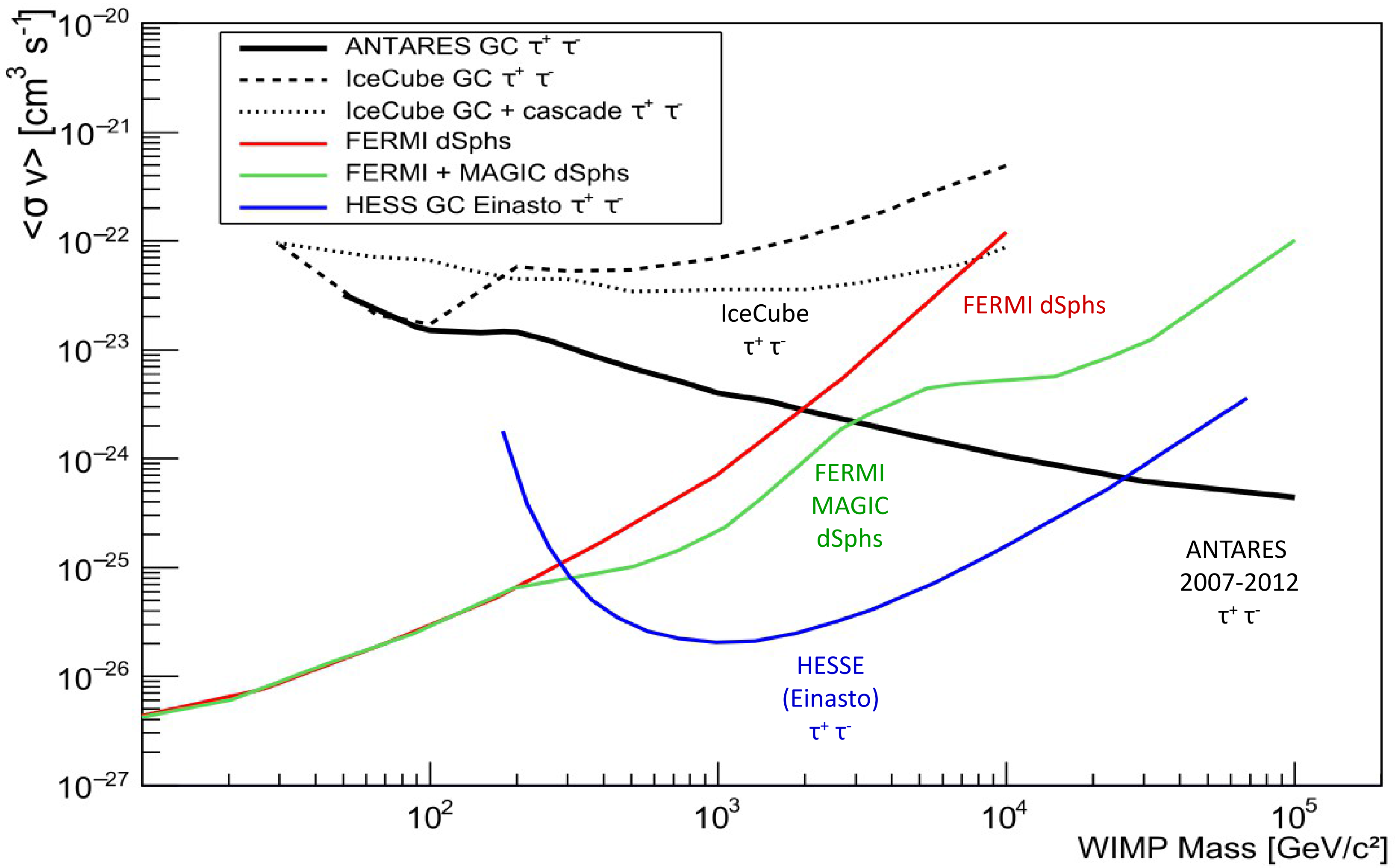
Einasto

$$\rho_{Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

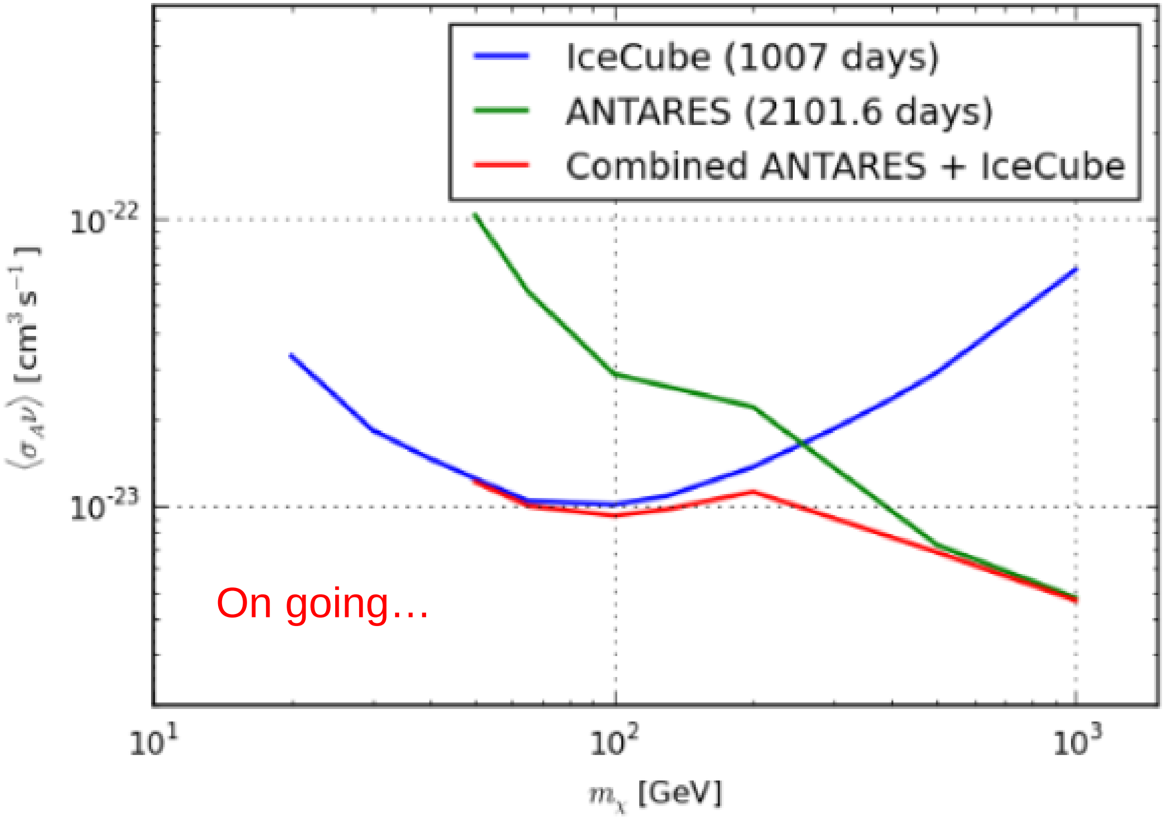


Cirelli et al., 1012.4515v4

Galactic Centre



Galactic Centre



Summary

ANTARES:

- 10 year experience. Thousands of ν's reconstructed as tracks and hundreds as showers). Excellent resolution (0.2° for tracks, down to 2° for showers!)
- Diffuse flux: a small excess at high energy compatible with a cosmic signal
- Dark matter searches in ν-tels are competitive for some scenarios and complementary to other searches
- Free lunch: "parasitic" use of ν-tels

KM3NeT:

- On the move!
  - 2 ARCA and 1 ORCA strings in water (teething problems, soon to be fixed)
- KM3NeT 2.0:
  - ESFRI Roadmap 2016, APPEC European Strategy 2017
  - Most of dark matter studies still lacking, but prospects are good